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Flexible Roofing Facility: 2002 Summer Test Results

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Flexible Roofing Facility: 2002 Summer Test Results

FSEC-CR-1411-03
July 2003

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Executive Summary

The Flexible Roof Facility (FRF) is a test facility in Cocoa, Florida designed to evaluate five roofing systems at a time against a control roof with black shingles and vented attic (Figure E-1). The testing is to evaluate how roofing systems impact summer residential cooling energy use and peak demand. In the summer of 2002, the following roofing systems were tested. The cell numbering is from left to right.

Cell #	Description
1	Galvalume®[1] unfinished 5-vee metal with vented attic
2	Double roof with radiant barrier, sealed attic and insulated roof deck (2nd year)
3	High reflectance ivory metal shingle with vented attic
4	Galvanized unfinished 5-vee metal with vented attic
5	Black shingles with standard attic ventilation (Control Test Cell)
6	White standing seam metal with vented attic

Figure E-1. Flexible Roof Facility in summer 2002 configuration.

All had R-19 insulation installed on the attic floor except in the configuration with the double roof (Cell #2) which had R-19 of open cell foam sprayed onto the bottom of the roof decking. The measured thermal impacts include ceiling heat flux, unintended attic air leakage and duct heat gain. We also developed a new analysis method to estimate total cooling energy use impacts of different roofing systems considering the various influences.

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[1] Galvalume is a quality cold-rolled sheet to which is applied a highly corrosion-resistant hot-dip metallic coating consisting of 55% aluminum 43.4% zinc, and 1.6% silicon, nominal percentages by weight. This results in a sheet that offers the best protective features characteristic of aluminum and zinc: the barrier protection and long life of aluminum and the sacrificial or galvanic protection of zinc at cut or sheared edges. According to Bethlehem Steel, twenty-four years of actual outdoor exposure tests in a variety of atmospheric environments demonstrate that bare Galvalume sheet exhibits superior corrosion-resistance properties.

The sealed attic double roof system (Cell #2) provided the coolest attic space of all systems tested (average maximum mid-attic temperature was 81.1ºF), and therefore also the lowest estimated impact due to return air leakage and duct conduction heat gains. However, it also had the highest ceiling heat flux of all strategies tested, reducing its improvement over the standard black shingle roof. It had the most modest reduction in space cooling at only 7% relative to the standard roof.

A major thrust of the testing for 2002 was comparative testing of metal roofing. Given the popularity of unfinished metal roofs, we tested both galvanized and Galvalume® roofs. Galvalume® roofs are reported to better maintain their higher solar reflectance than galvanized types. Average daily mid-attic maximum temperatures for the Galvalume® and galvanized metal roof systems were roughly similar (19.6ºF and 17.3ºF cooler than the control dark shingle respectively). Estimated total heat gains were also relatively close for both.

The highly reflective ivory metal shingle roof (Cell #3) provided the coolest peak attic temperature of all cells without roof deck insulation. Its average maximum daily mid-attic temperature was 93.3ºF (23.4ºF lower than the control dark shingle cell). While the ivory metal shingle roof's reflectance was slightly lower than the two metal roofs and white metal roof we observed evidence that the air space under the metal shingles provides additional effective thermal insulation.

We also estimated the combined impact of ceiling heat flux, duct heat gain and unintended attic air leakage from the various roof constructions. All of the alternative constructions produced lower estimated cooling energy loads than the standard vented attic with dark shingles (Figure E-2). The Galvalume® roof clearly provided greater reductions to cooling energy use than the galvanized roof even in the first summer of exposure.

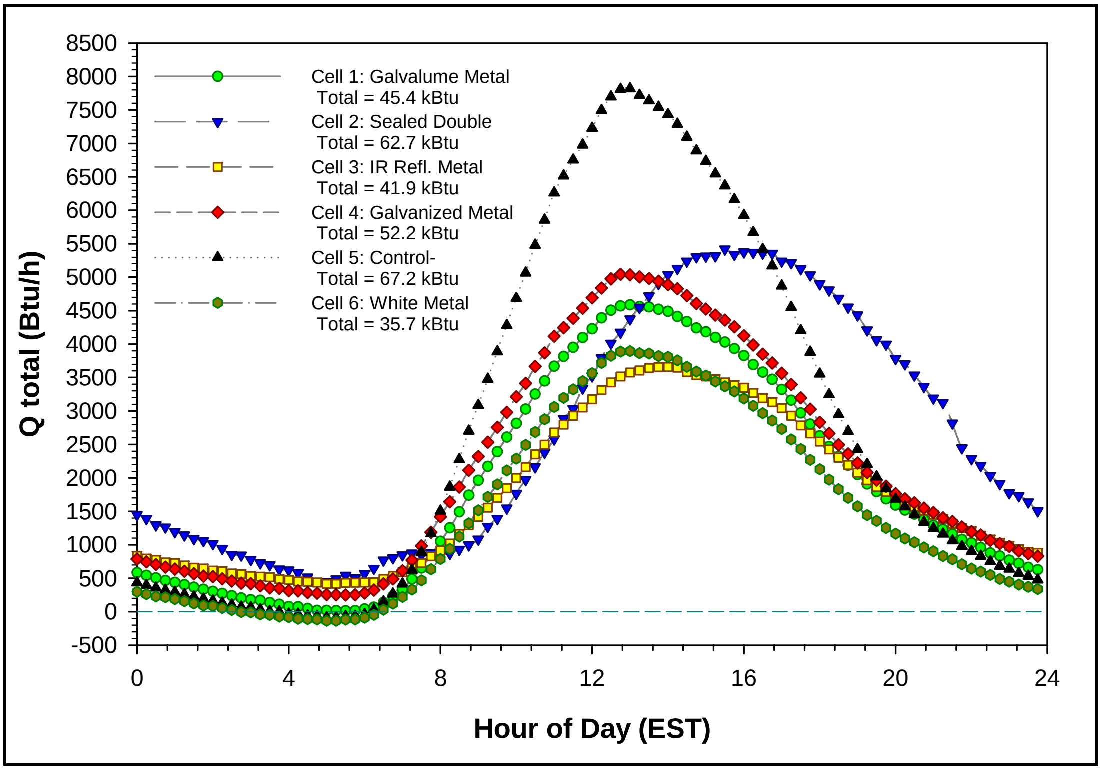

Figure E-2. Estimated combined impact of duct heat gain, air leakage from the attic to conditioned space and ceiling het flux on space cooling needs on an average summer day in a 2,000 ft^2 home.

An emerging fact from recent testing is that nighttime attic temperature and reverse ceiling heat flux have a significant impact on the total daily heat gain, particularly for the metal roofs. The rank order below shows the percentage reduction of roof/attic related heat gain and approximate overall building cooling energy savings:

Rank	Description	Roof Cooling Load Reduction	Overall Cooling Savings
1	White metal with vented attic:	47%	15%
2	High reflectance ivory metal shingle with vented attic	38%	12%
3	Galvalume® unfinished metal with vented attic:	32%	11%
4	Galvanized unfinished metal roof with vented attic	22%	7%
5	Double roof with sealed attic	7%	2%

The relative reductions are consistent with the whole-house testing recently completed for FPL in Ft. Myers (Parker et al., 2001). This testing showed white metal roofing having the largest reductions, followed by darker constructions.

Flexible Roofing Facility: 2002 Summer Test Results

Background

Improving attic thermal performance is fundamental to controlling residential cooling loads in hot climates. Research shows that the influence of attics on space cooling is not only due to the change in ceiling heat flux, but often due to the conditions within the attic itself and their influence on heat gain to duct systems and on air infiltration into the building. Figure 1 illustrates the fundamental thermal processes with a conventional vented attic.

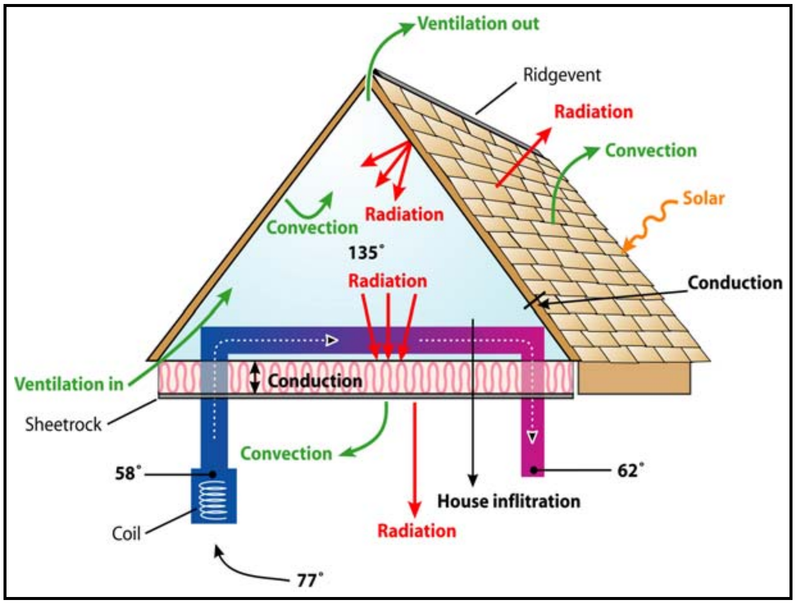

Figure 1. Vented attic thermal processes.

The importance of ceiling heat flux has long been recognized, with insulation a proven means of controlling excessive gains. However, when ducts are present in the attic, the magnitude of heat gain to the thermal distribution system under peak conditions can be much greater than the ceiling heat flux (Parker et al., 1993; Hageman and Modera, 1996).[2] This influence may be exacerbated by the location of the air handler within the attic space – a common practice in much of the southern US. The air handler is poorly insulated but has the greatest temperature difference at the evaporator of any location in the cooling system. It also has the greatest negative pressure just before the fan so that some leakage into the unit is inevitable. As evidence for this influence, a monitoring study of air conditioning energy use in 48 central Florida homes (Cummings, 1991) found that homes with the air handlers located in the attic used 30% more space cooling energy than those with air handlers located in garages or elsewhere.

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[1] A simple calculation illustrates this fact. Assume a 2,000 square foot ceiling with R-30 attic insulation. Supply ducts in most residences typically comprise a combined area of ~25% of the gross floor area (see Gu et al. 1996 and Jump and Modera, 1996), but are only insulated to between R-4 to R-6. With the peak attic temperature at 130ºF, and 78ºF maintained inside the house, a UA ΔT calculation shows a ceiling heat gain of 3,500 Btu/hr. With R-5 ducts in the attic and a 57ºF air conditioner supply temperature, the heat gain to the duct system is 7,300 Btu/hr if the cooling system ran the full hour under design conditions – more than twice the ceiling flux.

Buildings research also shows that duct system supply air leakage can lead to negative pressures within the house interior when the air handler is operating. The negative pressures can then result in hot air from the attic being drawn down into the conditioned space through gaps around recessed light fixtures or other bypasses from the attic to the interior. Attic air is often also directly drawn into the return air stream through leakage pathways (see Figure 2). These phenomena are commonly encountered in slab on grade homes in Sunbelt states in the U.S. where the dominant infiltration leakage plane from the exterior is through the ceiling.

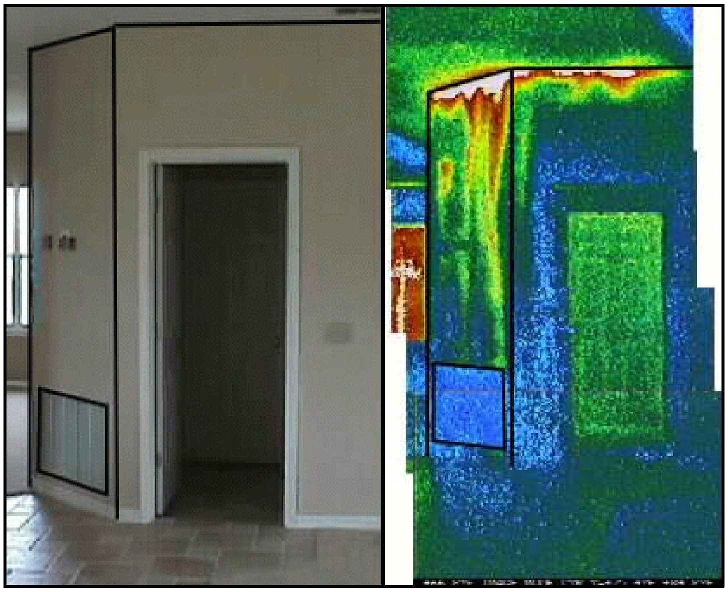
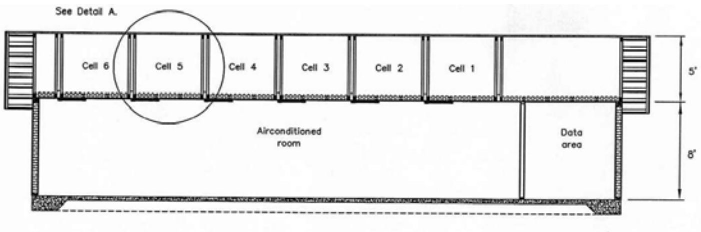


Figure 2. Thermograph of air being drawn from the attic to the air handler in a Florida house.

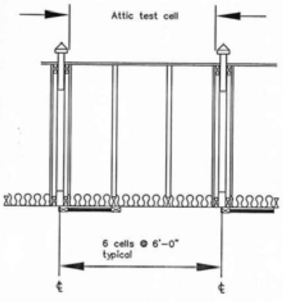
The impact of duct heat transfer and air leakage from the attic space shows that controlling attic air temperatures can be equally important as controlling ceiling heat flux alone. Consequently, in our assessment of the impact of different roof constructions on cooling related performance, we considered both ceiling flux and attic air temperature.

Test Facility Description and Objectives

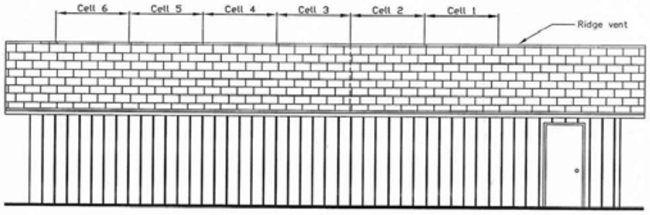
During the summer of 2002, tests were performed on six different residential plywood-decked roofing systems. The experiments were conducted at the flexible roof facility (FRF) located in Cocoa, Florida, ten miles (17 km) west of the Atlantic ocean on mainland Florida. The FRF is a 24 ft by 48 ft (7.3 x 14.6 m) frame building constructed in 1987 with its long axis oriented east-west (Figure 3). The roof and attic are partitioned to allow simultaneous testing of multiple roof configurations. The orientation provides a northern and southern exposure for the roofing materials under evaluation. The attic is sectioned into six individual 6 foot (1.8 m) wide test cells (detail A in Figure 3) spanning three 2 ft (0.6 m) trusses thermally separated by partition walls insulated to R-20 ft2-hr-°F/Btu (RSI-3.5 m2-K/W) using 3 inches (7.6 cm) of isocyanurate insulation. The partitions between the individual cells are also well sealed to prevent air flow cross-contamination. The gable roof has a 5/12 pitch (22.6°) and 3/4 inch (1.9 cm) plywood decking. On the attic floor, R-19 (RSI-3.3) unsurfaced batt insulation is installed between the trusses in all of the test bays (with the exception of Cell #2) in a consistent fashion. The attic is separated from the conditioned interior by 0.5 inch (1.3 cm) gypsum board. The interior of the FRF is a single open air conditioned space.



Section



Detail A.



North Side Elevation

The roof lends itself to easy reconfiguration with different roofing products and has been used in the past to examine different levels of ventilation and installation configurations for tile roofing (Beal and Chandra, 1995). Testing has also compared reflective roofing, radiant barriers and sealed attic construction (Parker and Sherwin, 1998). Appendix B list the test cell configurations over recent years. A black asphalt shingle roof on one of the test cells serves as a reference for other roofing types.

Our tests in 2002 addressed the following questions:

1) What is the performance (ceiling flux and attic air temperatures) of a standard black asphalt shingle roof with 1:300 ventilation (the control cell)?

2) How does a Galvalume® metal roof with vented attic compare to the control cell?

3) How does a galvanized metal roof with vented attic perform relative to Galvalume® and other roof types?

4) How does a higher IR reflectance ivory metal shingle roof function relative to the lower reflectance one installed the previous summer?

5) How does an innovative double roof construction with an insulated roof deck, radiant barrier and no attic ventilation perform compared with other types?

6) How does a white standing seam metal roof with vented attic perform relative to the other unfinished metal roof types?

Test Configuration and Instrumentation

To answer the above questions, we configured the test cells in the following fashion. Ages of roof construction are in parenthesis.

Cell #1: Galvalume® 5-vee unfinished metal roof; 1:300 vented attic (1st year)

Cell #2: Black asphalt shingles with vented double roof deck with radiant barrier and 6" foam insulation on underside of bottom roof deck; unvented attic (2nd year)

Cell #3: IR reflective ivory metal shingles; 1:300 soffit and ridge ventilation (1st year)

Cell #4: Galvanized 5-vee unfinished metal roof; 1:300 ventilation (1st year)

Cell #5: Black asphalt shingles; 1:300 soffit and ridge ventilation (control cell; 15 years old)

Cell #6: White standing seam metal; 1:300 vented attic (7 years old)

The final appearance of the facility as configured for testing is shown in Figure 4. All roofing materials were installed in a conventional manner, and according to manufacturer's specifications and current practice in the Central Florida area. Although raised wooden-battens type are sometimes used for metal roofing installations, current practice, with its focus on lower first costs, dictated a direct screwed application method for the metal roofs. Perforated vinyl soffit vents were used, and ridge vents for the vented cells were the "shingle vent" type with foam mesh or rigid plastic over the ridge outlet covered by shingles. The metal roofs had cap-type ridge vents.

Figure 4. Flexible Roof Facility in summer 2002 configuration.

In applicable test cells the free ventilation area was first estimated based on dimensional measurements and then verified by a fan pressurization test of the attic to estimate the equivalent leakage area, allowing for a consistent comparison. Test Cell # 2 with the insulated roof deck was sealed for the duration of the summer testing.

Samples of the new, unexposed roofing materials were sent to a laboratory to establish their integrated solar reflectance using ASTM Test Method E-903 (1996) and long wave emittance using ASTM E-408. Table 1 shows the laboratory reported values.

Note the large difference in the infrared emissivity of the unfinished metal roofs. Galvalume® (0.28) is much lower than the other painted metals (0.83), but galvanized roofs are much lower still (0.04). Generally, low emissive surfaces reach much higher temperatures since they do not readily give up collected heat back to the sky and its surroundings.

Table 1
Tested Roofing Material Solar Reflectances and Emittances*

Sample and Cell #	Solar Reflectance (%)	Long-wave emmittance
Cell #1: Galvalume® unfinished 5-vee metal	64.6%	0.28
Cell #2: Black shingle	2.7%	0.90
Cell #3: IR reflective ivory metal shingle	42.8%	0.83
Cell #4: Galvanized unfinished 5-vee metal	70.9%	0.04
Cell #5: Black shingle	2.7%	0.90
Cell #6: White metal standing seam	67.6%	0.83

* Laboratory tested values using ASTM E-903 and ASTM E-408.

Instrumentation for the project was extensive so the data can eventually validate a detailed attic simulation model. A number of temperature measurements using type-T thermocouples were made. Air temperature measurements were shielded from the influence of radiation. The temperature measurements included:

- Exterior surface of the roof and underlayment
- Decking underside
- Attic air at several heights within the attic
- Soffit inlet air and ridge vent exit air
- Insulation top surface
- Conditioned interior ceiling

The following meteorological data were taken:

- Solar insolation
- Aspirated ambient air temperature
- Ambient relative humidity
- Wind speed at a 33 ft (10 m) height
- Rainfall (tipping bucket)

All of the test cells were operational by June 5, 2002, at which point data collection began. The test cells were maintained in an unaltered state through the middle of September with continuous data collection.

Results

Attic Air Temperatures

The average summer day mid-attic air temperature profiles are shown in Figure 5. The profiles show the impact of the various roofing options in reducing summer cooling energy use associated with attic duct heat gains and loads from unintended air leakage coming from the attic zone.

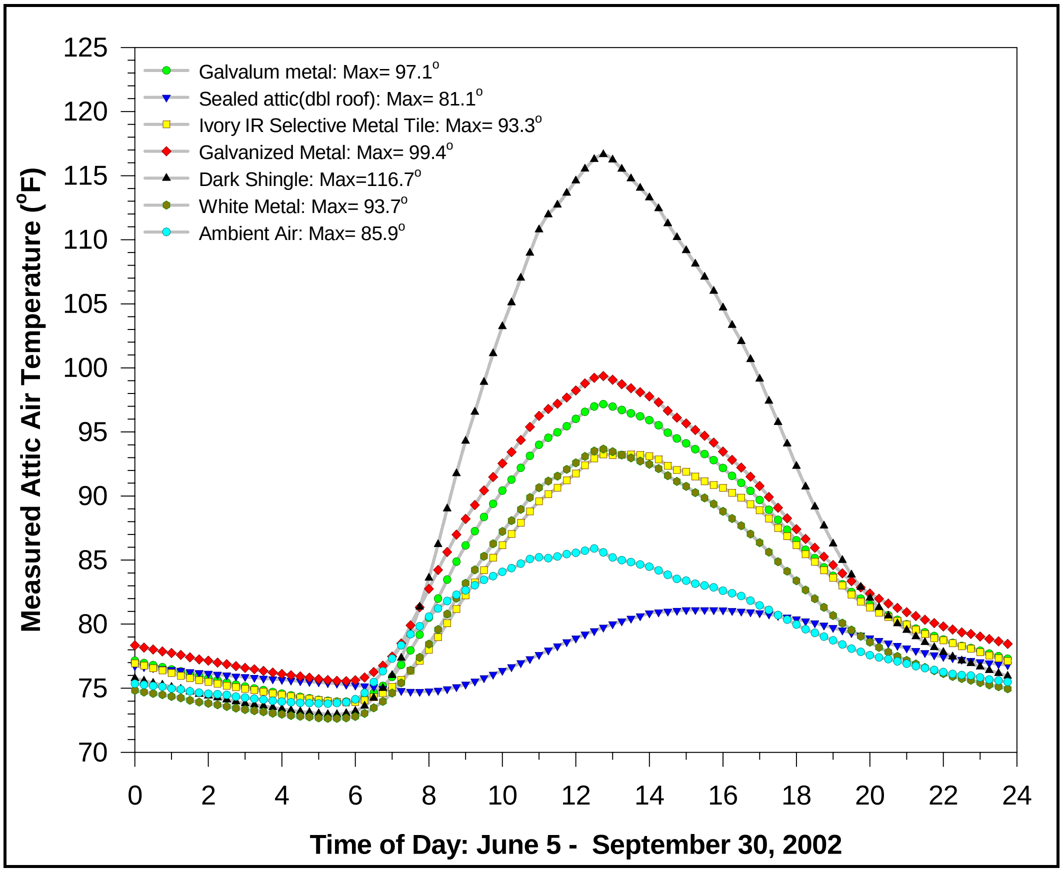


Figure 5. Measured average mid-attic air temperatures over the 2002 summer period.

The statistics for the average, minimum and maximum mid-attic air temperatures over the entire summer (hot average day) are summarized in Table 2. These results show that the sealed attic with the double roof provides the lowest overall mean attic temperatures (77.7°F) and hence lowest attic duct system heat gains and impact from return air leakage from the attic zone. The next most productive roof combination in this regard is Cell #6 with the vented white metal roof (81.0°F). Very similar to this performance is Cell #3 with the IR reflective metal shingle roof (82.3°F). Next best in performance is Cell #1 with the Galvalume® metal roof and vented attic at 83.6°F. The lower emissivity galvanized metal roof (Cell #4) averaging 85.2°F, is least beneficial relative to the standard attic which is at 89.1°F.

Table 2
FRF: Measured Mid-Attic Air Temperatures (ºF)
June 5 - September 30, 2002

	Description	**Mean**	**Standard**	**Minimum**	**Maximum**
Outdoor Air	Ambient Air	79.1	4.13	67.8	95.3
Cell #1	Galvalume® metal roof	83.6	7.95	67.7	110.9
Cell #2	Double roof deck (sealed attic)	77.7	2.16	72.9	84.8
Cell #3	High reflectance ivory metal shingle	82.2	6.76	68.5	105.9
Cell #4	Galvanized metal roof	85.1	8.16	68.3	113.7
Cell #5	Black shingle (control cell)	89.1	15.39	67.0	139.6
Cell #6	White metal roof	81.0	7.29	67.0	104.4

A rank order impact listing from best to worst summarizes these findings. Note that this ranking doesn't account for ceiling fluxes.

Rank Order on Reducing Cooling Season Impact Due to Duct System Heat Gains and Air Leakage (best to worst; note that the 2nd, 3rd, and 4th places in this list are very close in impact)

1. Sealed attic with double roof and insulated roof deck
2. White metal roof with vented attic
3. IR reflective ivory metal shingles with vented attic
4. Galvalume® metal roof with vented attic
5. Galvanized metal roof with vented attic
6. Black asphalt shingles with ventilated attic

Maximum Attic Air Temperatures

A comparison of the average daily maximum mid-attic air temperature for each cell against the average daily maximum ambient air temperature along with the corresponding temperature difference is shown in Table 3 below for the period between June 5 and September 30, 2002. These results show the success of the various roofing options in controlling duct heat gains and loads from unintended air leakage under averaged peak conditions for the period.

Table 3
FRF Average Maximum Attic and Ambient Air Temperatures

Cell No.	**Description**	**Average Max. Attic**	**Average Max. Ambient**	**Difference**
Cell #1	Galvalume® metal roof	97.1ºF	85.9ºF	+ 11.2ºF
Cell #2	Double roof deck (sealed attic)	81.1ºF	85.9ºF	- 4.8ºF
Cell #3	High reflectance ivory metal shingle	93.3ºF	85.9ºF	+ 7.4ºF
Cell #4	Galvanized metal roof	99.4ºF	85.9ºF	+ 13.5ºF
Cell #5	Black shingle (control cell)	116.7ºF	85.9ºF	+ 30.8ºF
Cell #6	White metal roof	93.7ºF	85.9ºF	+ 7.8ºF

Rank Order on Reducing Peak Impact Due to Duct System Heat Gains and Air Leakage

(best to worst; note that the 2nd and 3rd places in this list are very close in impact)

1. Sealed attic with double roof and insulated roof deck
2. High reflectance metal shingles with vented attic
3. White metal with vented attic
4. Galvalume® metal with vented attic
5. Galvanized metal with vented attic
6. Black asphalt shingles with ventilated attic

Note that Cell #2 with the sealed attic and insulation on the underside of the roof decking cannot be directly compared with the other cells as the others do not have roof deck insulation, but instead have insulation on top of the ceiling. Comparing the 2002 summer results with 1999 and 2000 Cell #2 results (sealed attic without double roof and RB) however, shows that the double roof/RB combination average maximum mid-attic temperature difference from ambient was 4.7°F lower than the same sealed attic without the double roof. Its maximum mid-attic temperature of 81.1°F was also 7.1°F lower than the averaged 1999 and 2000 results.

The highly reflective ivory metal shingle (Cell #3) provided the coolest attic of the cells without roof deck insulation. The average maximum mid-attic temperature in this case was 93.3°F, or 7.4°F higher than ambient. In 2001 the brown, IR reflective shingle on the test cell had a maximum attic air temperature that was 10.6°F higher than ambient. In 2000, the brown (non-highly reflective) metal shingle that was on the same cell had an average maximum attic temperature 13.5°F higher than ambient, while in 1999, a white highly reflective metal shingle on the same cell had an average maximum attic temperature 3.8°F higher than ambient. Thus, the new ivory colored IR reflective shingle is better than all the tested metal tile products except the white shingle.

The white standing seam metal (Cell #6) roof was vented during the 2002 summer test period. It was also cleaned prior to the test period to allow comparison with the pristine Galvalume® and galvanized metal roofs. Comparison with the previous year clearly shows the benefits of the cleaning and venting. In 2001 the average daily maximum attic air temperature above ambient was +14.4°F against +7.8°F in the summer of 2002.

Ceiling Heat Flux

Table 4 shows the statistics for ceiling heat fluxes over the 2002 summer period, and Figure 6 shows the ceiling flux data for the same period graphically. The uninsulated ceiling of the double roof with sealed attic (Cell #2) has a peak heat flux similar to that of the control (Cell #5), although with a significant time lag of over 3 hours. The mean heat flux for the double roof is 0.98 Btu/ft^2/hr, or 40% higher than the control. Also note from Figure 6 that the double roof has the highest nighttime flux values of all the cells. The highly reflective ivory metal shingle roof (Cell #3) has the lowest peak ceiling heat flux at 1.19 Btu/ft^2/hr, and also has a relatively low mean flux of 0.39 Btu/ft^2/hr, which is slightly higher than the white metal roof at 0.30 Btu/ft^2/hr. The vented white metal roof shows the lowest overall average heat flux and thus the lowest indicated ceiling influence on cooling for the overall period. The Galvalume® roof (mean heat flux of 0.43 Btu/ft^2/hr) performs similarly to the IR reflective roof with poorer performance for the galvanized metal roof (mean 0.53 /Btu/ft^2/hr).

Table 4
FRF Measured Ceiling Heat Fluxes (Btu/ft^2/hr)
June 5 - September 30, 2002

Cell #	Description	Mean	Stddev	Min	Max	Flux Change Relative to Cell #5
Flux 1	Galvalume® metal roof	0.43	0.43	-0.37	1.88	-38.6%
Flux 2	Double roof deck (sealed attic)	0.98	0.71	-1.11	3.33	+40.0%
Flux 3	High reflectance ivory metal shingle	0.39	0.23	-0.09	1.19	-44.3%
Flux 4	Galvanized metal roof	0.53	0.45	-0.32	2.09	-24.3%
Flux 5	Black shingle (control cell)	0.70	0.78	-0.38	3.32	Ref
Flux 6	White metal roof	0.30	0.38	-0.40	1.49	-57.1%

Rank Order on Reducing Cooling Season Ceiling Heat Flux (best to worst)

1. White metal with vented attic
2. High reflectance metal shingles with vented attic
3. Galvalume® metal roof with vented attic
4. Galvanized metal roof with vented attic
5. Black asphalt shingles with ventilated attic
6. Sealed attic with double roof and insulated roof deck

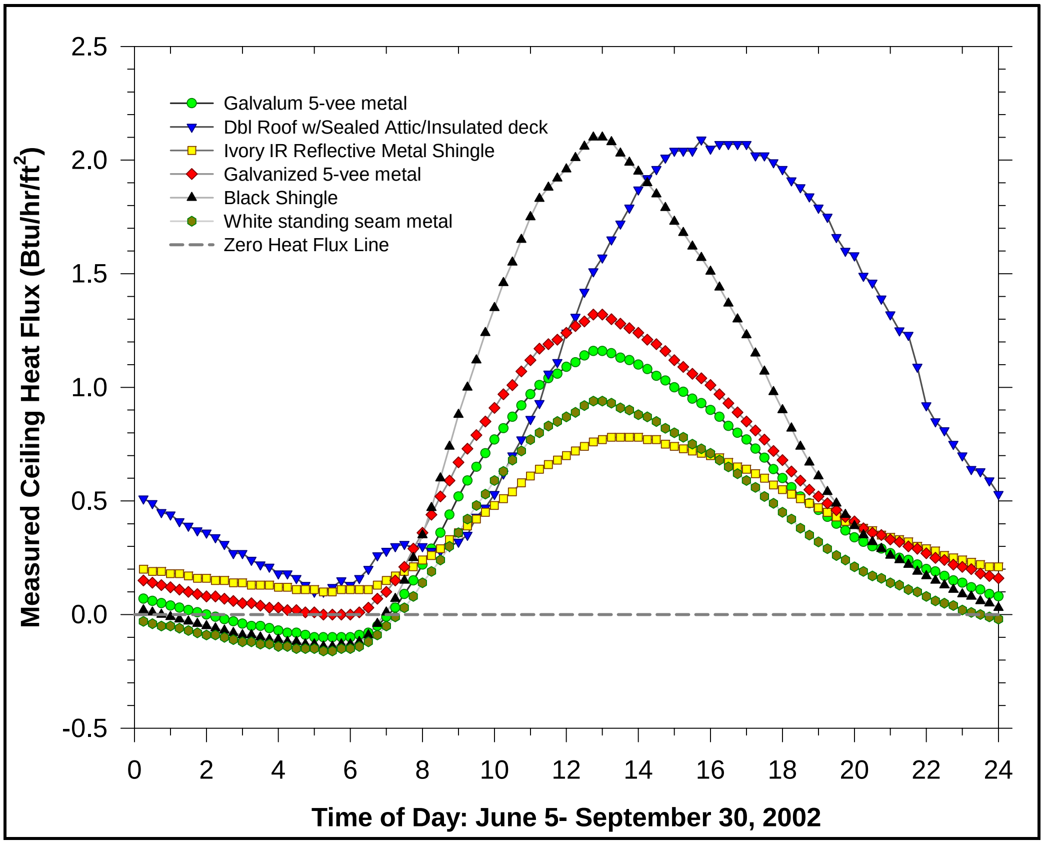


Figure 6. Measured average ceiling heat flux over the summer of 2002.

Estimation of Overall Impact of Roofing System

As described earlier in the report, the impact of a roofing system on cooling energy use in southern climates is often made up of three elements:

- Ceiling heat flux to the interior
- Heat gain to the duct system located in the attic space
- Air unintentionally drawn from the attic into conditioned space

The heat flux through the ceiling impacts the interior temperature and hence the thermostat which then calls for mechanical cooling. Thus, the heat flux impacts cooling energy use at all hours and affects the demand for air conditioning.

The other two influences, air leakage drawn from the attic into the conditioned space and heat gain to the duct system primarily occur only when the cooling system operates. Thus, the impact depends on the air conditioner runtime in a particular time interval. To obtain the average cooling system runtime, we used a large set of residential cooling energy use data which has only recently been made public domain. This data comes form 171 homes monitored in the Central Florida area where the 15-minute air conditioner power was measured for over a year (Parker, 2002).

For each site, the maximum demand during summer was also recorded to determine the maximum cooling system power. Thus, it is possible to determine the diversified runtime fraction by dividing the average air conditioner system power by its maximum demand. This calculation was made by averaging the air conditioner and air handler power for all sites and dividing by the average maximum summer demand, which was 3.96 kW.

Figure 7 shows the maximum average cooling system runtime is approximately 55% at 4 PM and is at its minimum of 15% at 6 AM. It is important to note that this is an average summer day as determined by evaluating all data from June - September inclusive. It does not represent an extreme summer day condition.

With the runtime fraction determined for an average home in Central Florida for the summer, it is then possible to estimate the impact of duct heat gain and attic return air leakage with some working assumptions.

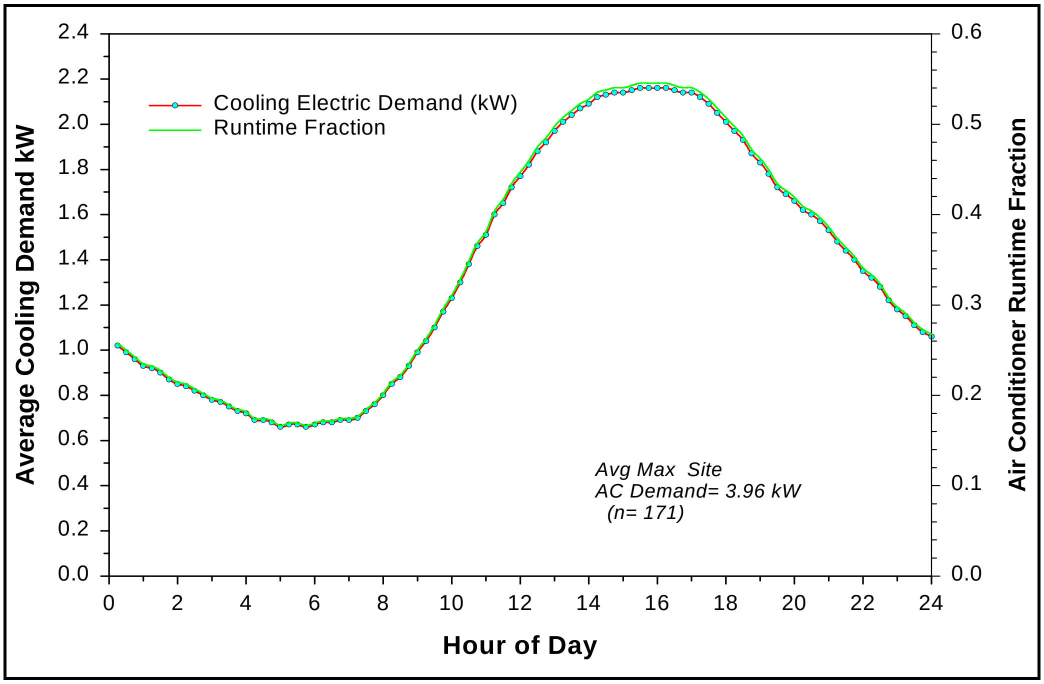


Figure 7. Average air conditioner power and average runtime fraction over an average summer day in a large sample of Central Florida homes.

To estimate the overall impact of each roofing system, we first assume a typical single-story home with 2,000 square feet of conditioned floor area. Then three equations are defined to estimate the individual impacts of duct heat gain (Q_{duct}), attic air leakage to conditioned space (Q_{leak}) and ceiling heat flux ($Q_{ceiling}$).

For duct gains, heat transfer is estimated to be:

$$Q_{duct} = (Area_{duct}/R_{duct}) * (T_{attic} - T_{duct,air}) * RTF$$

Where:

Q_{duct} = cooling load related to duct gains (Btu/hr)
$Area_{duct}$ = 25% of conditioned floor area or 500 ft^2 (Gu et al., 1996, see Appendix G)
R_{duct} = R-6 flex duct
T_{attic} = attic air temperature measured in FRF test cells
$T_{duct, air}$ = typical air temperature leaving evaporator (58°F)
RTF = typical air conditioner runtime fraction as determined from data in Figure 7

Generally, the duct heat gains will favor the double roof sealed attic construction which results in lower surrounding attic temperatures. For attic air leakage to conditioned space, the estimated heat transfer is:

$$Q_{leak} = Flow * PctLeak * PctAttic * 1.08 * (T_{attic} - T_{interior}) * RTF$$

Where:

Q_{leak} = cooling load related to unintentional air leakage to conditioned space from attic (Btu/hr)

Flow = air handler flow; 4-ton system for 2000 ft^2 home, 400 cfm/ton = 1600 cfm
PctLeak = duct leakage assumed as 10% of air handler flow
1.08 = air specific heat density product per CFM (Btu/hr CFM °F)
PctAttic = 33% of duct leakage is assumed to be leakage from the attic (see Figure 1)
T_{attic} = attic air temperature measured in FRF test cells
$T_{interior}$ = interior cooling temperature (75°F)
RTF = typical air conditioner runtime fraction as determined from data in Figure 7

Heat flux is proportional to the house ceiling area and is estimated as:

$$Q_{ceiling} = Area_{ceiling} * Q_{flux}$$

Where:

$Area_{ceiling}$ = 2,000 ft^2
Q_{flux} = measured ceiling heat flux from FRF data

So the total heat gain impact of a roofing systems is estimated to be:

$$Q_{tot} = Q_{duct} + Q_{leak} + Q_{ceiling}$$

Figure 8 shows the combined roofing system heat gain estimated for 2,000 square foot houses with each of the six roofing systems tested this summer. Figure 9 breaks down the Q_{duct}, Q_{leak} and $Q_{ceiling}$ components of Figure 8 for the Cell #5 control roof to show the relative contribution of each component. Note that the combined estimated duct leak gain and duct conduction gain is approximately equal to the ceiling flux gain.

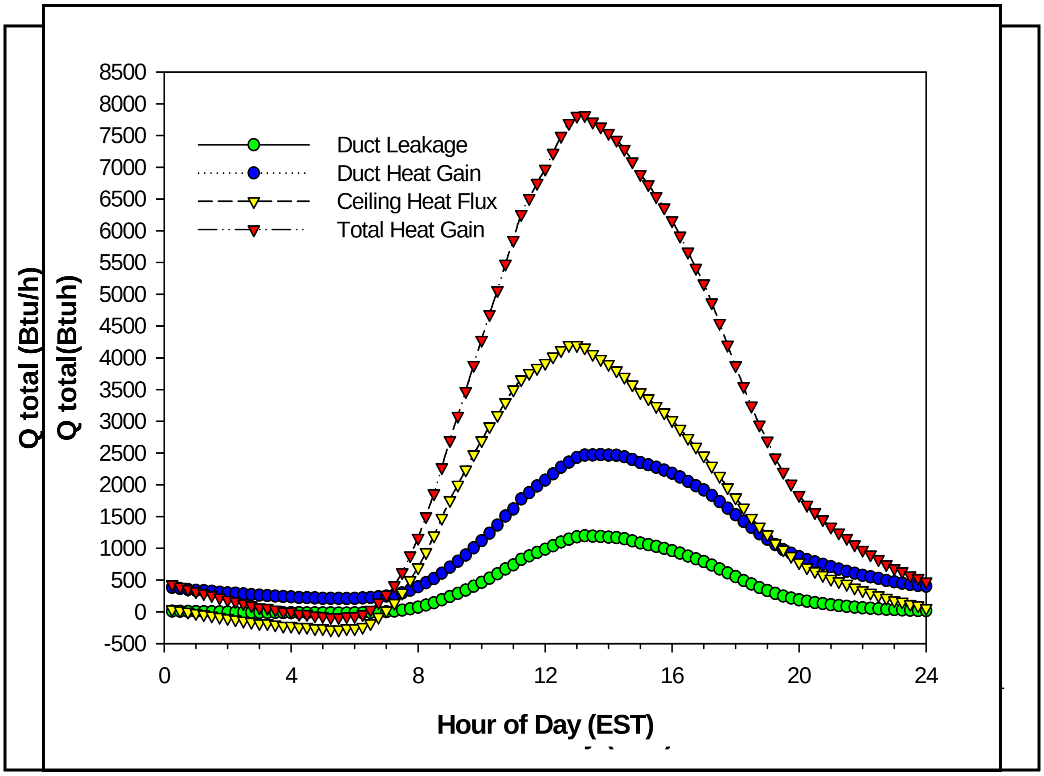


Figure 8: Estimated combined impact of duct heat gain, air leakage from the attic to the conditioned space and ceiling heat flux on space cooling load on an average summer day in a 2,000 ft^2 home.

Figure 9: Components of estimated daily heat gain due to duct heat gain, air leakage from the attic to the conditioned space and ceiling heat flux for Cell #5.

Table 5 shows the relative impact on space cooling and performance relative to the control (Cell #5).

Table 5
Combined Ceiling Heat Flux, Duct Heat Gain and Attic Duct Leakage Impact in a 2000 sqft Home

Case		**Average Daily kBtu from Roof/Attic**	**Percent Heat Gain Difference Relative to Control**
Cell #1	Galvalume® metal roof	45.4	-32.4%
Cell #2	Double roof deck (sealed attic)	62.7	- 6.7%
Cell #3	High reflectance ivory metal shingle	41.9	-37.6%
Cell #4	Galvanized metal roof	52.2	-22.3%
Cell #5	Black shingle (control cell)	67.2	0.0%
Cell #6	White metal roof	35.7	-46.9%

All of the alternative test cells do better than the standard reference cell. The estimation shows that the white metal roof with ventilation (Cell #6) does best, followed by the high reflectance metal shingle roof (Cell #3). The Galvalume® metal roof with a ventilated attic provides about a 30% reduction in heat gain. The galvanized roof with its significantly lower emissivity provides only about a 20% heat reduction. The sealed attic with the double roof provides the lowest reduction. The is primarily a result of the much greater measured heat flux across the uninsulated ceiling.

Conclusions

The 2002 FRF test results suggest indicators of the relative thermal performance of various roofing systems under typical Florida summer conditions. Within the body of the report, we describe the various relative impacts to ceiling heat flux, unintended attic air leakage and duct heat gain. Here we provide a summary extrapolated heat gain analyses as a useful means of estimating total cooling energy benefits of different roofing systems.

The vented standing seam white metal roof had the lowest total system heat gain of all the tested roofs since its ceiling heat flux was much lower than that with the sealed attic construction. Its attic temperatures were also much lower than the conventional dark shingled attic test cell. The average daily maximum attic temperature was only about 94ºF. The overall cooling related savings from this roof construction was on the order of 47% of roof-related heat gain.

In this year's tests, the sealed attic double-roof system (Cell #2) provided the coolest attic space of all systems tested (average maximum daily mid-attic temperature was 81.1ºF) and therefore also the lowest estimated duct leakage and duct conduction heat gains. However, it also had the highest ceiling heat flux of all strategies tested, reducing its improvement over the standard dark shingle roof in the control home to only a modest 6.7% reduction to roof-related cooling energy. Note also that since this double roof configuration provided significantly cooler attic temperatures than the standard sealed attic tested during the previous two summers, higher total heat gains should be anticipated from standard sealed attics. Thus, this system may represent an optimal system for sealed attics which use dark roofing.

A major thrust of the testing for 2002 was to evaluate popular unfinished metal roofing systems and compare those with other types. We tested an unfinished Galvalume® 5-vee metal roof with attic ventilation as well as a galvanized 5-vee metal roof in an identical configuration. The galvanized roof has a high solar reflectance, but a much lower infrared emittance (0.04) which we expected to hurt its performance. The monitoring bore out this fact. The Galvalume® metal roof both ran cooler and produced much less roof related heat gain. The Galvalume® roof provided a 32% reduction in roof and attic related heat gain over the summer as compared with a 22% reduction for the galvanized roof. Moreover, as galvanized roofs are known to lose their solar reflectance rapidly over time as the zinc surface oxidizes, we expect to see a further decrease in performance in a second season of testing. Although white metal performs best, the Galvalume® metal roofing surface is a good second choice for cooling related climates, and does nearly as well as the IR selective ivory metal shingles.

At an average maximum mid-attic temperature of 93.3ºF (23.4ºF lower than the control dark shingle cell), the highly reflective ivory metal shingle roof (Cell #3) provided the coolest peak attic temperature of all cells without double roof deck. While the ivory metal shingle roof's reflectance was somewhat lower than the white metal roof's, it is likely that the air space under the metal shingles provides additional effective insulation. Both of these characteristics probably come into play to help it achieve lower peak attic temperatures, while the additional insulating effect likely causes its slightly higher nighttime attic temperatures.

We also estimated the combined impact of ceiling heat flux, duct heat gain and air being unintentionally drawn from the attic into conditioned space for the various roof constructions. These estimates indicate that all of the tested roof configurations yield lower heat gains during the summer cooling season than the control roof which has dark shingles with R-19 ceiling insulation and 1:300 ventilation. One emerging fact from the recent testing is that nighttime attic temperature and reverse ceiling heat flux have a significant impact on the total daily heat gain, and therefor constructions that produce lower evening attic temperatures benefit from these effects. The rank order is shown below and in Figure 10 with the percentage reduction of roof/attic related heat gain (and the approximate overall building cooling energy savings)[3].

	Roof-related Savings	Approximate Overall Savings
• White metal with vented attic:	46.9%	15%
• High reflectance ivory metal shingle with vented attic:	37.6%	12%
• Galvalume® unfinished metal roof with vented attic:	32.4%	11%
• Galvanized unfinished metal roof, vented attic	22.3%	7%
• Double roof with sealed attic	6.7%	2%

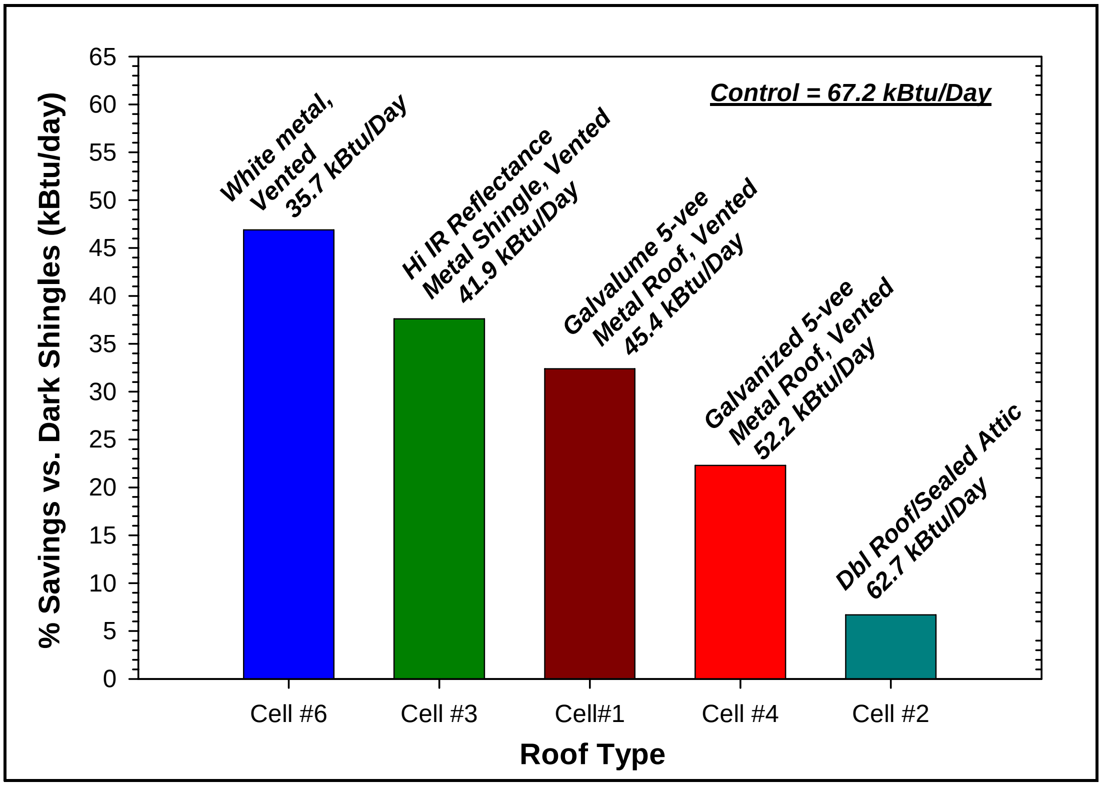


Figure 10. Percentage savings in daily total roof/attic related heat gain.

The rank order of the reductions are consistent with the whole-house roof testing which was recently completed for FPL in Ft. Myers (Parker et al., 2001) which showed white metal roofing as having the largest reductions. However, these results represent the first time that popular unfinished metal roofs have been comparatively ranked.

References

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[3] Since the roof/attic ceiling heat flux, duct heat transfer and duct leakage likely comprise about a third of the total home cooling loads, the above values are modified to approximate the overall impact.

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Appendix A

Long Term Weather Data at the Flexible Roof Facility

Long Term Weather Data at the Flexible Roof Facility

For the analysis, we examined how the long term summer weather has varied at the Flexible Roof Facility from 1997 - 2002. The purpose was to create a method that can be used to normalize data on attic temperatures and ceiling heat fluxes that will allow comparison over various roofing systems from one year to the next.

This was done by examining how temperatures and heat fluxes varied from one year to the next when evaluated from June - September. The results, which are shown below, evidence little variation from one year to the next, both for ambient air temperature and in Cell #5, the reference cell, over the last five years. Ceiling heat fluxes vary a little more, but not that much.

Table A-1
Variation of Weather and Reference Cell Conditions from 1997 - 2002

		------------ Cell #5 -------------			
Year	Avg. Ambient Temp (F)	Avg. Attic Temp (F)	Max Attic Temp (F)	Avg. Flux (Btu/ft2/hr)	Max Flux (Btu/ft2/hr)
97	79.1	90.8	141.9	0.73	3.34
98	81.7	92.6	142.3	0.84	3.39
99	79.9	90.9	142.3	0.77	3.41
00	80.1	91.2	141.2	0.78	3.36
01	79.3	90.4	143.4	0.74	3.48
02	79.1	89.1	139.6	0.70	3.32

The year 1998 stands out as an outlier, but that is expected (record breaking hot summer). Our working idea would be to ratio temperature and flux data to 1997 for each quantity to normalize for summer weather in future analysis of data from the FRF when evaluated over successive summer seasons.

Appendix B

FRF Test Cell Summer Configuration History

FRF Test Cell Summer Configuration History
(**Bold** = changed cell in that year)

1997
1 White barrel tile, standard ventilation
2 Dark shingles with RBS, 1:150 ventilation
3 Dark shingles with RBS, 1:300 ventilation
4 Red terra cotta tile, standard ventilation
5 Dark shingles with standard ventilation (Control)
6 White standing seam metal with standard ventilation

1998
1 White tile, standard ventilation
2 Dark shingles, sealed attic with R-19 Icynene deck insulation
3 Dark shingles with RBS, 1:300 ventilation
4 Red terra cotta tile, standard ventilation
5 Dark shingles with standard ventilation (Control)
6 White standing seam metal with standard ventilation

1999
1 White tile, standard ventilation
2 Dark shingles, sealed attic with R-19 Icynene deck insulation
3 White metal shingles with standard ventilation
4 Red terra cotta tile, standard ventilation
5 Dark shingles with standard ventilation (Control)
6 White standing seam metal with standard ventilation

2000
1 White tile, standard ventilation
2 Dark shingles, sealed attic with R-19 Icynene deck insulation
3 Dark brown metal shingles with standard ventilation
4 Red terra cotta tile, standard ventilation
5 Dark shingles with standard ventilation (Control)
6 White metal standing seam roof with standard ventilation

2001
1 White barrel tile, unvented
2 Dark shingles, double roof, sealed attic with R-19 Icynene deck insulation
3 IR reflective brown metal shingles with standard ventilation
4 Red terra cotta tile, standard ventilation
5 Dark shingles with standard ventilation (Control)
6 White metal standing seam roof, unvented

2002

1 **Galvalume® 5-vee Roof, vented**
2 Dark shingle, double roof, sealed attic with R-19 Icynene deck insulation
3 **IR reflective ivory metal shingles, vented**
4 **Galvanized 5-vee roof, vented**
5 Dark shingles with standard ventilation (Control)
6 **White standing seam roof, vented**

Appendix C

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